GAMMA RAY BURST HOST GALAXIES HAVE 'NORMAL' LUMINOSITIES

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ABSTRACT

The galactic environment of Gamma Ray Bursts can provide good evidence about the nature of the progenitor system, with two old arguments implying that the burst host galaxies are significantly subluminous. New data and new analysis have now reversed this picture: (A) Even though the first two known host galaxies are indeed greatly subluminous, the next eight hosts have absolute magnitudes typical for a population of field galaxies. A detailed analysis of the 16 known hosts (ten with red shifts) shows them to be consistent with a Schechter luminosity function with $R^* = -21.8 \pm 1.0$, as expected for normal galaxies. (B) Bright bursts from the Interplanetary Network are typically 18 times brighter than the faint bursts with red shifts, however the bright bursts do not have galaxies inside their error boxes to limits deeper than expected based on the luminosities for the two samples being identical. A new solution to this dilemma is that a broad burst luminosity function along with a burst number density varying as the star formation rate will require the average luminosity of the bright sample ($>6 \times 10^{58} ph \cdot s^{-1}$ or $>1.7 \times 10^{52} \cdot erg \cdot s^{-1}$) to be much greater than the average luminosity of the faint sample ($\sim 10^{58} ph \cdot s^{-1}$ or $\sim 3 \times 10^{51} erg \cdot s^{-1}$). This places the bright bursts at distances for which host galaxies with a normal luminosity will not violate the observed limits. In conclusion, all current evidence points to GRB host galaxies being normal in luminosity.

Subject headings: gamma rays: bursts

1. Introduction

The key puzzle of Gamma Ray Bursts (GRBs) is the nature of their central engine. Observations of the burst afterglows can provide some information about the cause of the burst, but this is limited since the explosion will destroy much evidence. Another type of knowledge that will be useful is to identify the environment of the burster, since this will provide information about the progenitor. For example, if GRBs appear outside galaxies then models with binary systems containing collapsed stars that can have high ejection velocities will be preferred, while if GRBs appear preferentially in high luminosity galaxies with rapid star formation then models with very massive progenitors will be preferred. So useful questions are "Do GRBs appear within normal galaxies?" and "What is the luminosity function of the GRB host galaxies?"

In the past, two arguments have been presented that made strong cases that most GRBs appeared either outside normal galaxies, in systematically subluminous hosts, or at high luminosities (Schaefer 1999; Band, Hartmann, & Schaefer 1999). The first argument is that GRB970228 and GRB970508 (the first two identified GRB hosts) are in the bottom $\sim 1\%$ of the luminosity weighted Schechter luminosity function, with this result being unlikely unless the GRB hosts are systematically subluminous. The second argument is that a dozen very bright bursts seen with the Interplanetary Network (IPN; Hurley 1986; Hurley et al. 1993) have no galaxies in their small error boxes to B magnitudes from 20 to 24, whereas the hosts should have been easily visible if the bursters reside in normal host galaxies for the luminosities allowed by LogN-LogP studies.

In the past year, new burst red shifts have greatly changed the situation from that presented in the previous paragraph. Also, I here propose an alternative solution for the lack of sufficiently-bright hosts for the bright bursts. This paper presents these two new

analyses, with the conclusion that GRBs reside in normal host galaxies whose luminosities are distributed as a normal Schechter luminosity function.

2. Hosts of Faint Bursts

The first two discovered GRB hosts (for GRB970228 and GRB970508) are galaxies at the bottom of the luminosity function. But now we have data for hosts on sixteen GRBs with optical transients or radio transients (OT/RT) to provide arc-second positions and ten of these have measured red shifts (see Table 1). This much larger sample can answer the question of "What is the luminosity function for the host galaxies of faint bursts?"

An approximate answer to this question can be obtained by merely examining the derived absolute magnitudes of the hosts as taken from Table 1. We see that the first two GRB hosts are fortuitously the least luminous hosts by about one magnitude. This means that the early argument for subluminous hosts based on GRB970228 and GRB970508 is wrong due to a rather unlikely coincidence. Further, we see that the typical R-band absolute magnitude is around -21, a value which is comparable to the R^* value characteristic of the R-band Schechter luminosity function. R^* is approximately -21.2 mag in the local vicinity for a Hubble constant of $65 km \cdot s^{-1} \cdot Mpc^{-1}$ (Lin et al. 1996). So to first order, the host galaxies of faint GRBs have a normal luminosity.

However, a variety of effects and biases can affect this conclusion: The probability of a detected burst yielding a red shift and an apparent magnitude for the host depends on the burst distance, the burst luminosity, and the host's absolute magnitude. So our sample in Table 1 will be biased towards luminous hosts for which a red shift is more likely to be measured. Also, the bursts in Table 1 have a typical red shift of ~ 1, so that effects due to the values of cosmological parameters $(\Omega_m, \Omega_\Lambda)$ and the K-corrections for both bursts and

hosts will affect the conclusion. Hence, the analysis given in the previous paragraph needs to be improved.

An improved analysis is to model all these effects and biases with a Monte Carlo calculation to produce a simulated catalog of bursts containing subsets with red shifts and host apparent magnitudes. I have adopted a Hubble constant of $65 km \cdot s^{-1} \cdot Mpc^{-1}$ in a flat Universe with $\Omega_m = 0.3$. I take the burst number density to follow the star formation rate as given by Madau, Pozzetti, & Dickinson (1998). The burst luminosity function is taken as the usual truncated power law with slope -2, dynamic range of 1000, and a minimum luminosity of $10^{57} ph \cdot s^{-1}$, to be consistent with the observed time dilation, red shifts, and LogN-LogP curve (Deng & Schaefer 1999) as well as the light curve variability (Ramirez-Ruiz & Fenimore 1999). The host luminosity function was taken to have the shape of the Schechter luminosity function with slope $\alpha = -1$ and a characteristic R-band absolute magnitude, R^*, which is a free parameter. Based on the events in Table 1 and the LogN-LogP curve, I will approximate the probability of getting an arc-second position for an observed burst as rising linearly from zero for P_{256} values ranging between 0.5 to 5.5 $ph \cdot s^{-1} \cdot cm^{-2}$. Similarly, the probability of measuring an apparent magnitude for a host galaxy is taken to be 0.7 if the burst has an arc-second position and a host brighter than R=25.7 mag. The K-corrections for the host are taken for those of an Sb galaxy as given by Rocca-Volmerange & Guideroni (1988). The K-corrections for the burst are taken for a count spectrum varying as E^{-2} (Schaefer et al 1994; 1998).

What parameters should be used to compare the model with the observations? A comparison of apparent magnitudes allows for more measured values from Table 1 than would a use of absolute magnitudes. Reasonable aggregate parameters for model comparisons are the median and the standard deviation for the apparent magnitudes of detected bursts (24.88 and 1.49 mag; see Table 1).

Few observed apparent magnitudes are currently known, so the shape of the host luminosity function cannot yet be well constrained. Nevertheless, the observed scatter in R_{host} is a function of the shape and can indicate consistency with the luminosity-weighted Schechter luminosity function adopted. For reasonable models, the typical standard deviation of R_{host} is 2.4 mag, although this varies widely for samples of 16 bursts. The observed standard deviation (1.49 mag) is not surprisingly smaller than these model values, so as yet there is no inconsistency with the shape of the Schechter function. The $<R_{host}>$ value for 16 bursts varies with a standard deviation of $2.4/\sqrt{16}$ or 0.60 mag, so the target for the model is 24.88 ± 0.60 mag.

For what values of R^* does the model reproduce the observed distribution of host apparent magnitudes? Figure 1 displays the model predictions as a function of the adopted R^*. An acceptable range of R^* is then from -21.2 to -22.4 mag, with the best value being around -21.8 mag.

However, uncertainties in the model input parameters will enlarge the acceptable range of R^*. This can be quantified by calculating the change in the model $<R_{host}>$ when one input parameter is changed over some plausible range (with the luminosity function shifted such that the observed $<LogL>$ is held constant). A change in Ω_m from 0.3 to 1.0 makes the average R_{host} fainter by 0.34 mag. A change of the Hubble constant will change both the model $<R_{host}>$ and the R^* value for normal galaxies to the same degree, with these effects canceling out. A change in the average slope of the GRB count spectrum from E^{-2} to $E^{-1.5}$ changes $<R_{host}>$ by less than 0.1 mag. A shift in the intrinsic burst luminosity function by a factor of two changes $<R_{host}>$ by 0.1 mag and 0.3 mag for brighter and fainter bursts respectively. Even large changes in the shape of the burst luminosity function move $<R_{host}>$ by less than 0.2 mag. So an uncertainty of ~ 0.4 mag in the model $<R_{host}>$ arises from uncertainties in the model input parameters. Then, the range of acceptable R^*

values increases to from -20.8 to -22.8, so the final model estimate of R^{*} is -21.8 ± 1.0 mag.

This derived R^{*} value is easily consistent with normal galaxies, yet is inconsistent with greatly subluminous hosts. The uncertainty in R* is larger than desirable due to the few available GRB hosts known to date and to significant uncertainties in the conditions of the high red shift Universe. These will be improved with time. For now, the conclusion is that GRBs appear to have host galaxies of normal luminosity.

3. Hosts of Bright Bursts

The bursts with optical or radio transients are typically rather faint, with the median P_{256} being only a factor of 3 above the BATSE completeness threshold. These GRBs are greatly fainter than the bursts positioned with the IPN (see Fig. 2). For a fair comparison, the sixteen OT/RT bursts (Table 1) can be compared with the sixteen IPN bursts with the smallest error boxes (Schaefer et al. 1998). The median IPN burst is 18 times brighter than the median OT/RT burst.

For many reasonable models, the IPN bursts should thus be ~ 4 times closer than the OT/RT events and then will be substantially immune to many problems that plague the interpretation of the high red shift OT/RT events (uncertainties in the K-corrections, the cosmological parameters, the dust extinction, and the galaxy luminosity function). For some purposes, the IPN burst sample might then be more important than the OT/RT sample because the low red shift Universe can be readily interpreted.

Schaefer (1999) and Band, Hartmann, & Schaefer (1999) both examine the limits on Rhost for the IPN GRBs, with the conclusion that the hosts can have normal luminosities (i.e., be drawn from the usual luminosity-weighted Schechter luminosity function) only if

the average burst luminosity is greater than $6 \times 10^{58} ph \cdot s^{-1}$ (LogL=58.8). This directly contradicts fits to the LogN-LogP curve (Horváth, Mészáros, & Mészáros 1996), the time dilation of burst light curves (Deng & Schaefer 1999), as well as the observed luminosities for the OT/RT bursts (see Table 1). Possible solutions to this dilemma were that the GRBs were ejected from their birth galaxy or that the host galaxies are systematically subluminous for some reason. Neither solution now seems plausible.

I would like to point out another solution which fits well with currently popular ideas. The dilemma arises because the bright IPN bursts were plausibly assumed to have the same mean luminosity as the faint OT/RT bursts. However, if GRBs simultaneously have a broad luminosity function and their number density increases greatly with red shift, then the bright bursts will have a much greater average luminosity than will faint bursts. That is, if the OT/RT events have $LogL \approx 58.0$ while the IPN events have $LogL > 58.8$, then the host galaxies of the IPN bursts will have $R_{host} \sim 24$ and be fully consistent with the limits in Schaefer et al. (1998).

To provide a quantitative evaluation of this idea, I have calculated the average luminosities and red shifts for bursts with peak fluxes brighter than some threshold for a variety of burst luminosity functions. The required integrals were performed numerically for red shifts over the range 0-6 with bins of 0.01. The luminosity distances were calculated for a flat Universe with $\Omega_m = 0.3$ (hence $\Omega_\Lambda = 0.7$) with a Hubble constant of $65 km \cdot s^{-1} \cdot Mpc^{-1}$. The star formation rate was taken from Madau, Pozzetti, & Dickinson (1998) as deduced from the rest-frame UV luminosity density. The K-corrections were made assuming that the average burst count spectrum is an E^{-2} power law, as indicated in Fig. 46 of Schaefer et al. (1994) and Figure 4 of Schaefer et al. (1998). The burst luminosity function was taken either as a log-normal distribution or as a truncated power law. The characteristic widths of these were allowed to vary widely, but the average luminosity was set such that

$<LogL>$ for a population observed with $P_{256}>1ph \cdot s^{-1}$ was 58.34 (see Table 1). Figure 3 displays the results for the truncated power law from the previous section as well as for two widths of a log-normal luminosity function.

Both power law and log-normal distributions give similar results, in that samples of bright bursts will be much more luminous than samples of dim bursts. The one-sigma scatter in the observed LogL values varies from 0.5 to 0.9, which is comparable to that seen in Table 1. The mean red shift of bright burst samples is much higher than would be expected from simple scaling by $P_{256}^{-0.5}$ from the red shift of a faint burst sample, for example the log-normal luminosity function with width 1.0 has a ratio of $<z>$ equal to 2.0 for samples with P_{256} greater than 1.0 and $30ph \cdot s^{-1} \cdot cm^{-2}$. In the extreme case of a very broad power law with $\sim L^{-2}$, the $<z>$ will be roughly a constant.

An interesting result from these calculations is that the luminosity function of the *observed* GRBs is roughly log-normal for any broad *intrinsic* shape. That is, both log-normal and power law input functions produce apparently log-normal output functions. With a broad log-normal input function, the observed $<LogL>$ will be over ten times larger than the intrinsic $<LogL>$ so that the shape of the intrinsic distribution near and below its peak is irrelevant. This result is due to a cutoff in the observed events on the low luminosity side by the small volume of space near enough for weak bursts to be detectable and a cutoff on the high luminosity side by the rapid decrease in the number of strong bursts. Unfortunately, an implication is that an approximately log-normal observed luminosity distribution (see Table 1 or Ruiz-Ramirez & Fenimore 1999) can only tell us that the intrinsic luminosity function is broad.

For broad luminosity functions, the $<LogL>$ for observed bursts is determined by the overall slope of the intrinsic luminosity function. Thus for $LogL \sim 58$, the GRB luminosity

function must scale close to L^{-2} regardless of the behavior at high and low luminosity.

The primary point of Fig. 3 is that the average luminosity of the bright bursts is greatly larger than for the faint bursts. The most important comparison is for bursts with $P_{256}{>}0.85 ph \cdot s^{-1} \cdot cm^{-2}$ (the BATSE completeness threshold which is relevant for logN-LogP studies and for the OT/RT bursts in Table 1) versus bursts with $P_{256}{>}30 ph \cdot s^{-1} \cdot cm^{-2}$ (for the IPN bursts). For the three broad luminosity functions in Fig. 3, the ratio of luminosities for these two thresholds is 8.3, 4.0, and 13.5. That is, the average luminosity of the IPN bursts is roughly an order of magnitude brighter than for the OT/RT and BATSE bursts. This means that for OT/RT and BATSE bursts with $<LogL>\sim 58.0$ (Horváth, Mészáros, & Mészáros 1996; Deng & Schaefer 1999; Ruiz-Ramirez & Fenimore 1999; Table 1) then the IPN bursts likely have $<LogL>\sim 59.0$. This is completely consistent with the lack of hosts in IPN boxes to deep limits (Schaefer 1999).

In summary, the two original arguments that hosts are subluminous are now shown to be incorrect, with the new conclusion that hosts are just normal galaxies without need of any special environment for the GRB progenitors.

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Table 1: Host galaxy data for bursts with optical or radio positions.

GRB	P^{a}_{256}	Transient^{b}	$z(Method)^{c}$	$Log_{10}L^{d}$	R^{e}_{host}	M^{f}_{host}	$Ref.$
	$ph \cdot s^{-1} \cdot cm^{-2}$			$ph \cdot s^{-1}$	mag	mag	
970228	10.0	O	0.695 (He)	58.38	24.96	-18.92	g
970508	1.2	O, R	0.835 (Aeax)	57.65	25.65	-19.13	h
970828	~ 1.5	R	0.958 (He)	57.90	24.41	-20.93	i
971214	2.3	O	3.418 (He)	59.45	25.56	-24.46	j
980326	~ 3	O	$\cdots$	$\cdots$	>27.1	$\cdots$	k
980329	13.3	O, R	$\cdots$	$\cdots$	25.94	$\cdots$	l
980425	1.1	SN	0.0085 (Ha)	53.24	~ 13	~ -20	m
980519	4.7	O, R		$cdots$	25.40	$\cdots$	n
980613	0.5	O	1.097 (He)	57.57	23.85	-22.07	o
980703	2.6	O, R	0.966 (Aea)	58.04	22.43	-22.94	p
981226	~ 0.4	R		$\cdots$	24.79	$\cdots$	q
990123	16.6	O, R	1.600 (Aa)	59.50	23.73	-23.85	r
990308	1.6	O		$\cdots$	>25.7	$\cdots$	s
990506	22.2	R		$\cdots$	24.7	$\cdots$	t
990510	10.2	O, R	1.619 (Aa)	59.30	>27.0	>-20.59	u
990712	~ 2.3	O	0.430 (Aea)	57.25	21.71	-20.63	v
Median:	2.5		0.96	57.97	24.88	-20.78^{y}	
Average:	3.1^{w}		1.09^{wx}	58.34^{x}	24.86^{x}	-21.35^{y}	

Notes: [a]Peak flux in the 50-300 keV band over a 256 ms time interval. Values are from the BATSE online catalog (http://gammaray.msfc.nasa.gov/batse/grb/) or by scaling from the SAX peak flux. [b]O indicates that an optical (or near infrared) transient was seen, R is for a radio transient, and SN is for a supernova. [c]A or H indicates whether the afterglow or the host galaxy was used to measure the red shift; while a, e, or x indicates optical absorption lines, optical emission lines, or x-ray emission lines. [d]The burst luminosity is calculated from $P_{256} \cdot 4\pi D_l^2$, where D_l is the luminosity distance for a $\Omega_m = 0.3$ flat Universe (hence $\Omega_\Lambda = 0.7$) and a Hubble constant of $65 km \cdot s^{-1} \cdot Mpc^{-1}$. To find an average equivalent luminosity with units $erg \cdot s^{-1}$ from 30-2000 keV (Fenimore et al. 1993), divide by approximately 3.6×10^6 (or subtract 6.55 from the logarithm). [e]The R-band magnitude for the host galaxy after a correction for the absorption from our Milky Way galaxy. [f]The absolute R-band magnitude of the host galaxy based on the tabulated magnitudes and red shifts. K-corrections were applied for Sb galaxies with no E-corrections as taken from Rocca-Volmerange & Guideroni (1988). For GRB971214 at z=3.412, I adopt a K-correction of 2.5 mag. At z=1, the range of K-corrections is 0.7 mag over the classes of spiral galaxies. [g]Djorgovski et al. 1999b; Fruchter et al. 1999b; Castander & Lamb 1999. [h]Metzger et al. 1997; Bloom et al. 1998b. [i] Djorgovski 1999. [j]Kulkarni et al. 1998. [k] Bloom et al. 1999b. [l] Djorgovski 1999. [m] Galama et al. 1998. [n] Bloom et al. 1998a. [o] Djorgovski et al. 1999a. [p] Djorgovski et al. 1998; Vreeswijk et al. 1999b. [q] Frail et al. 1999. [r] Hjorth et al. 1999; Halpern et al. 1999. [s] Schaefer et al. 1999. [t] Bloom et al. 1999a. [u] Vreeswijk et al. 1999a; Fruchter et al. 1999a. [v] Galama et al. 1999; Kemp et al. 1999. [w] The geometric mean was used. [x] The averages exclude GRB980425 since its red shift and luminosity can plausibly be considered to be from a separate population. [y] With E-corrections for the host galaxy from Rocca-Volmerange & Guideroni (1988), the median M_{host} is -20.06, the average Mhost is -19.90 and the standard deviation of Mhost is 1.42 mag.

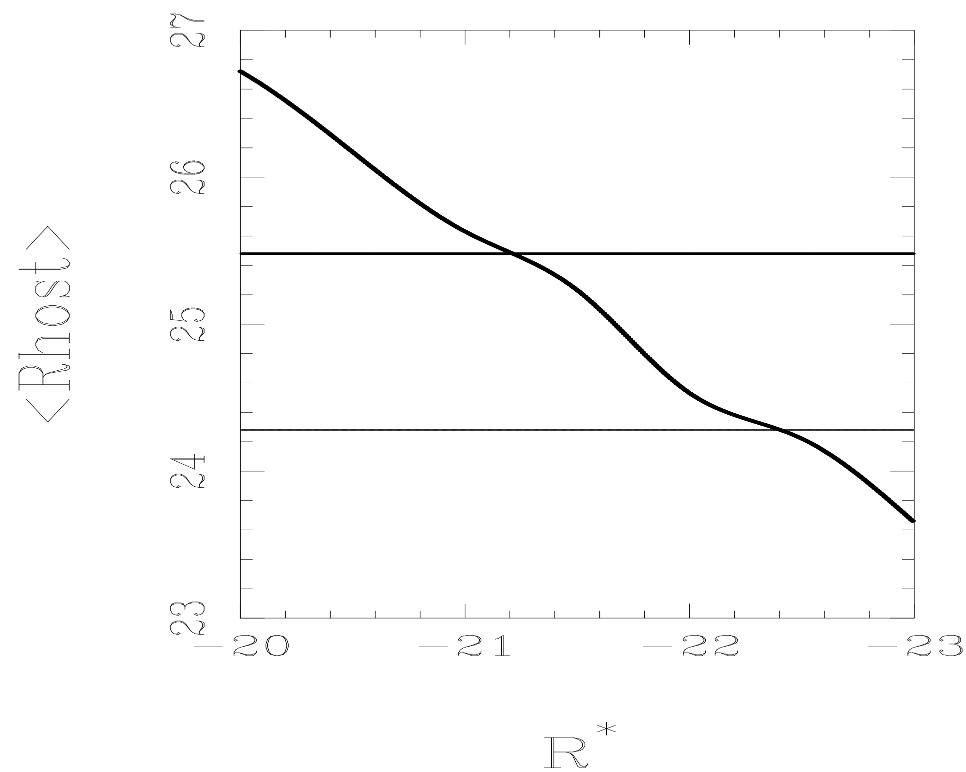

Fig. 1.— Average host magnitude for both observed bursts and the model. The analysis of host magnitudes has moved past consideration of just the first two known hosts as well as simple calculations of the average host absolute magnitude. The graph below compares the results from realistic Monte Carlo simulated burst catalogs (the sloped curve) with the range of uncertainty for the observed values (between the two horizontal lines; 24.88 ± 0.60 mag). The one free parameter in the model is the R^* value which characterizes the host galaxy luminosity, with $R^* = -21.2$ (for a Hubble constant of $65 km \cdot s^{-1} \cdot Mpc^{-1}$). The acceptable range for is then $-21.2 > R^* > -22.4$ for the adopted model parameters, although this range is increased to $-20.8 > R^* > -22.8$ when allowance is made for plausible uncertainties in the adopted model parameters. From this, we see that GRB hosts are apparently of normal luminosity and certainly not greatly subluminous on average (despite the first two known hosts being greatly subluminous).

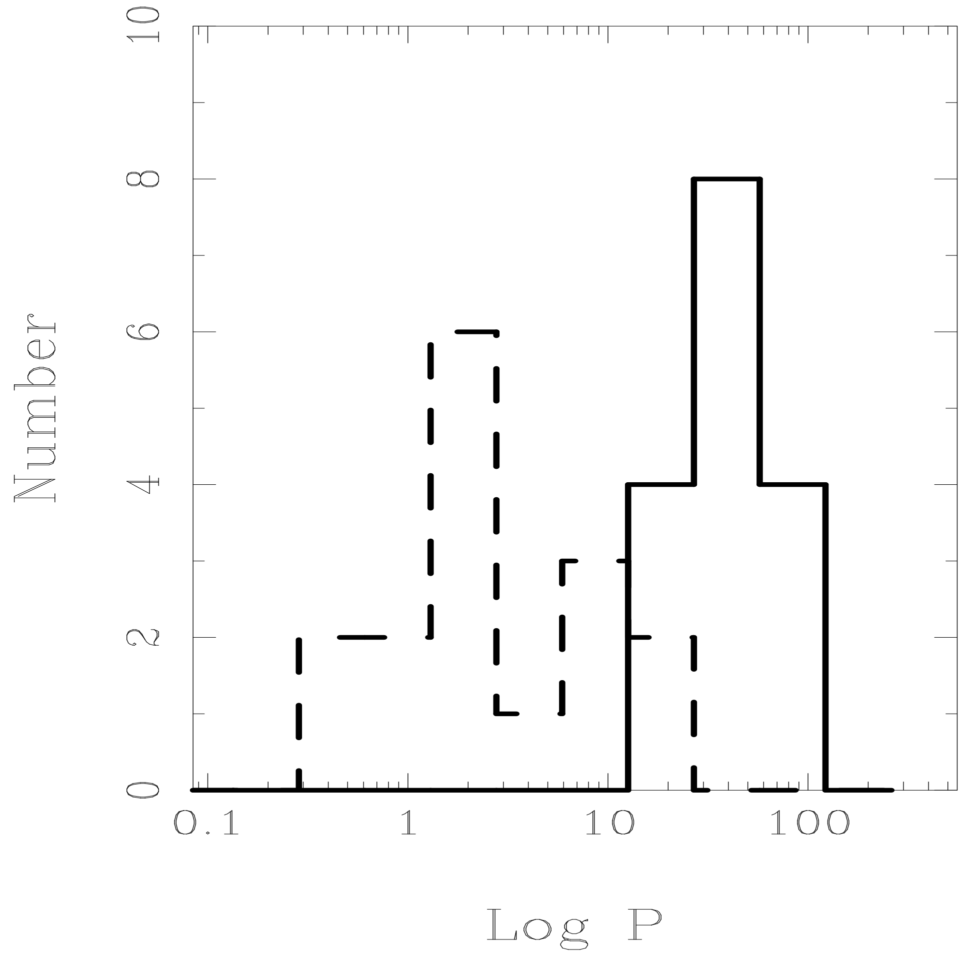

Fig. 2.— The IPN bursts are ~ 18 times brighter than the GRB/OT bursts. This histogram shows the distribution of P_{256} for two samples of sixteen bursts; (a) the smallest IPN bursts shown with the solid line and (b) the OT/RT bursts with arc-second positions from Table 1 shown with the dashed line. The two distributions are nearly separated, with the OT/RT bursts greatly fainter than the IPN bursts. The medians of the two distributions have a ratio of 18.

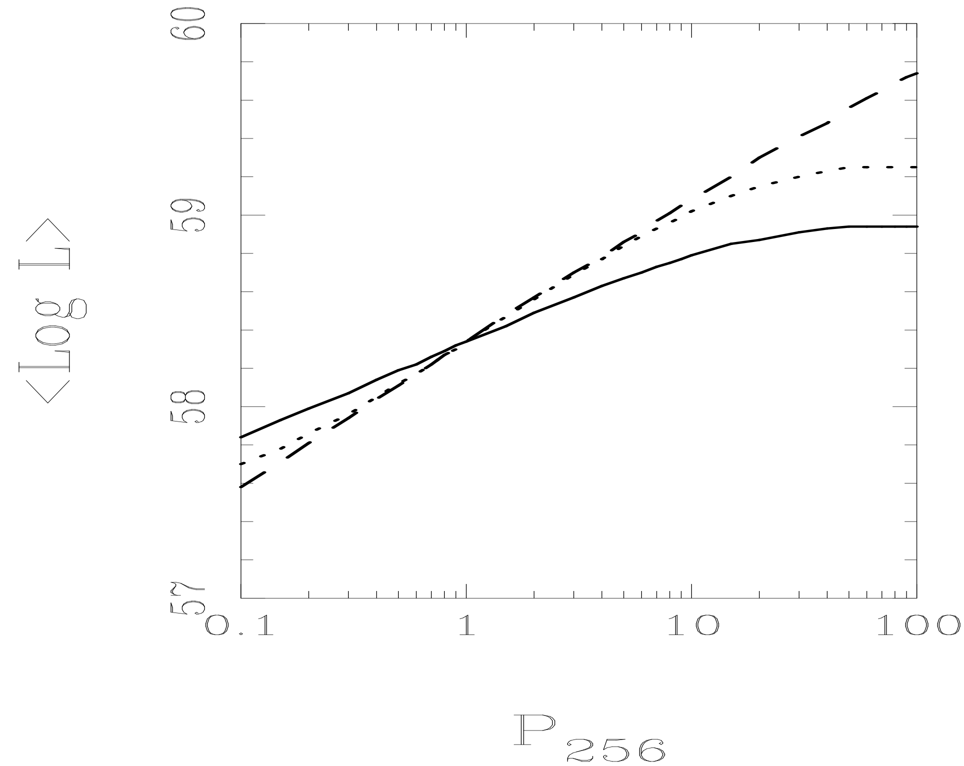

Fig. 3.— Bright bursts are much more luminous than faint bursts. The average luminosity ($<log_{10}(L)>$ with units of $ph \cdot s^{-1}$) for observed bursts depends sharply on the threshold P_{256} (in $ph \cdot s^{-1} \cdot cm^{-2}$ from 50-300 keV) value for the sample despite a constant intrinsic luminosity function. The intermediate curve is for a truncated power law luminosity function as used in section 2. Two curves are for a log-normal intrinsic luminosity function of width 1.0 (i.e. the typical dispersion is a factor of ten; the shallow curve), and of width 2.0 (i.e. the typical dispersion is a factor of one hundred; the steep curve). A comparison between BASTE or OT/RT bursts (threshold $P_{256} = 0.85 ph \cdot s^{-1} \cdot cm^{-2}$) and IPN bursts (threshold $P_{256} = 30 ph \cdot s^{-1} \cdot cm^{-2}$) must account for the factor of ~ 10 difference in average luminosity. This realization resolves the discrepancy that faint bursts have $<LogL>$ around 58.0 (based on time dilation of the light curves, the LogN-LogP curve, and the few known red shifts) while bright bursts have $<LogL>$ greater than 58.8 (based on the lack of host galaxies to deep limits).